

Introduction: A fundamental process of planetary differentiation is the segregation of metal-sulfide and silicate phases, leading eventually to the formation of a metallic core. Asteroidal meteorites provide a glimpse of this process frozen in time from the early solar system. While chondrites represent starting materials, iron meteorites provide an end product where metal has been completely concentrated in a region of the parent asteroid. A complimentary end product is seen in metal-poor achondrites that have undergone significant igneous processing, such as angrites, HED's and the majority of aubrites. Metal-rich achondrites such as acapulcoite/lodranites, winonaites, ureilites, and metal-rich aubrites may represent intermediate stages in the metal segregation process. Among these, acapulcoite-lodranites and ureilites are examples of primary metal-bearing mantle restites, and therefore provide an opportunity to observe the metal segre-

gation process that was captured in progress. In this study we use bulk trace element compositions of acapulcoites-lodranites and ureilites for this purpose.

Discussion: For a given starting mass, metal-silicate segregation occurs in three stages each brought about by an increase in temperature: (1) textural coarsening of silicate and metal grains, (2) formation and migration of metal-sulfide partial melts, and (3) migration of refractory metal *en masse*. Silicate melting and melt migration accompanies, and may facilitate, this stage. The first stage can be observed in the metamorphic stages (3-6) of ordinary chondrites which experienced an increase in mean grain size and mineral equilibrium with progressive metamorphism at subsolidus temperatures. During this stage, siderophile elements remain unfractionated in the bulk mass. The second stage begins as temperatures exceed the Fe-Ni-S cotectic (~980°C). Sulfur-

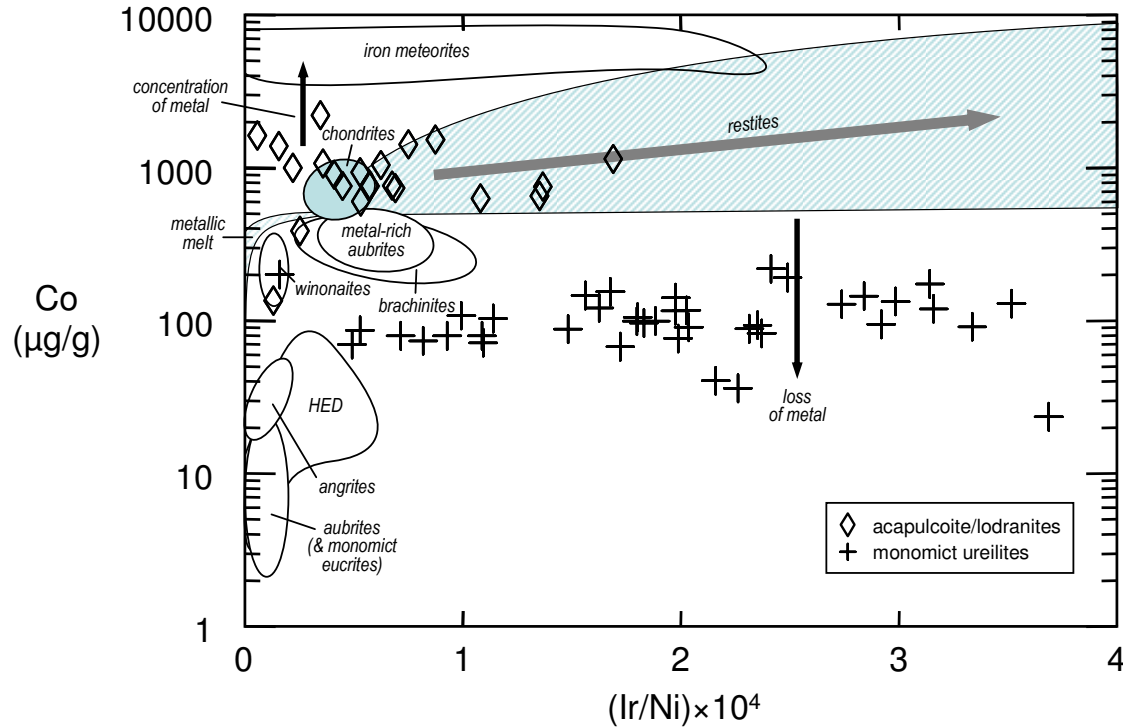


Figure 1. Siderophile elements Ir/Ni (by weight) vs. Co for asteroidal meteorites. Ir/Ni increases through extraction of metallic partial melts while Co concentration is an indication of metal abundance. Field labeled “chondrites” encompasses all known chondrite types. Field for restite composition is based on batch melt extraction from a CI chondrite parent material at melt S contents of 0-44 mol% and with 0-20% coeval loss of surrounding silicate. A field for complimentary aggregate melts (in a constant relative volume of silicate) is also shown. Assuming a chondritic precursor material, compositions below these fields require additional loss of metal while those above require concentration of metal. Acapulcoite/lodranite and ureilite compositions are indicated by symbols. Generalized data fields are drawn for other meteorite types to encompass >90% of available data. Metal-rich aubrites are distinguished by a separate field from other aubrites. The lower aubrite field overlays and is nearly identical to that of monomict eucrites. The HED field is taken to represent the vast majority of uncontaminated group members. Diogenites occupy the portion of the field in view while monomict eucrites are overlain by the lower aubrite field and encompass nearly the same portion of the diagram. A few cumulate eucrites plot slightly to the right of the field. Data compiled from numerous sources.

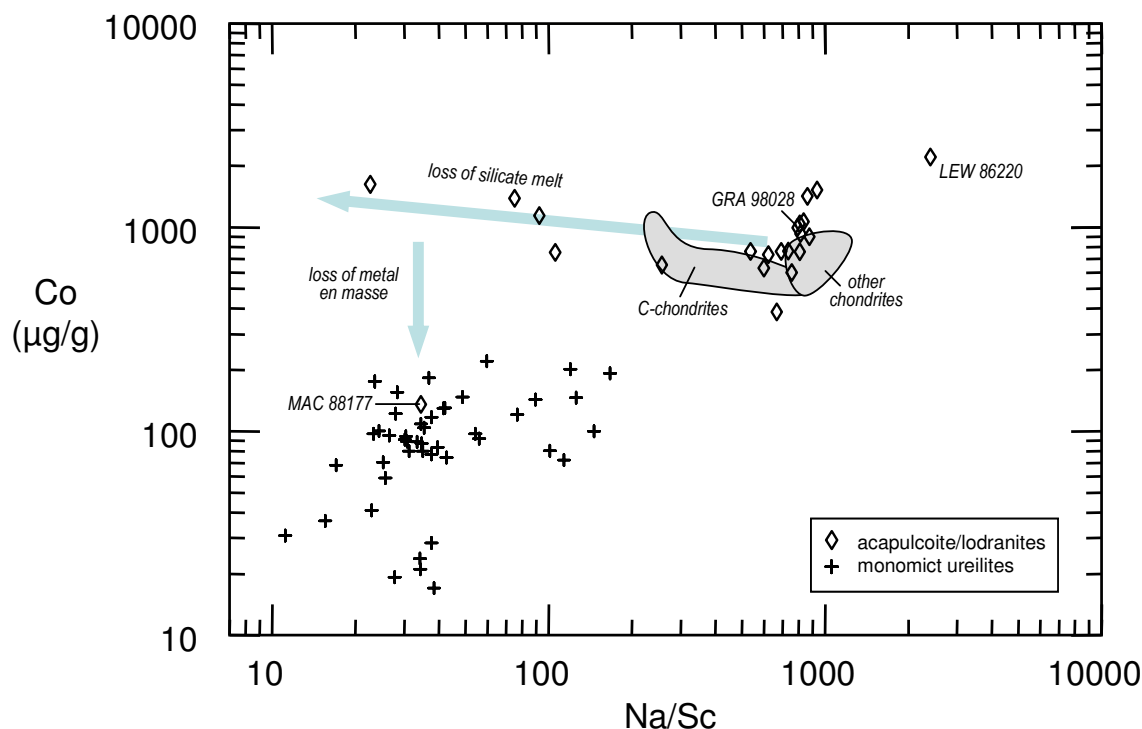


Figure 2. Processes of silicate partial melt extraction, indicated by decreasing Na/Sc, and extent of metal loss, indicated by Co concentration, for acapulcoite-lodranites and monomict ureilites. GRA 98028 is the most texturally primitive acapulcoite [1] and represents a logical starting composition on the figure. MAC 88177 is a lodranite which has lost much or all of its original metal. LEW 86220 is an acapulcoite enriched with a basaltic melt [2,1]. Data compiled from numerous sources.

rich partial melts form and can continue to form until S is exhausted from the system. Combined textural and chemical evidence suggest that these melts readily migrate into and out of portions of the parent asteroid even in the absence of silicate melt migration and even at temperatures below the silicate solidus [2,3]. At this stage, siderophile elements become fractionated according to their solid-liquid partitioning behavior. Figure 1 shows elevated Ir/Ni in acapulcoite-lodranites and ureilites consistent with removal of S-rich metallic partial melts, which would have very low Ir/Ni. All other groups of stony asteroidal achondrites are characterized by near-chondritic or sub-chondritic Ir/Ni. Stage 3 is the near complete removal of metal from silicate. If S is effectively exhausted during stage 2, the remaining solid metal is extremely refractory, and will not melt until temperatures well above the silicate solidus. Complete loss of this remaining Fe,Ni-metal alloy by strictly mechanical means would require high degrees of silicate partial melting, deformation, or both [4]. Low siderophile element concentrations in monomict ureilites, represented by Co in Figure 1, suggest that much of their refractory metal component has indeed been lost. Ureilites are estimated to have experienced ~30% depletion of silicate partial melts to account for their chemical and mineralogic composition [5,6]. All acapulcoite-lodranites with the exception of MAC 88177 appear to retain a significant metal component. MAC 88177 is also unique in that it appears to have experienced a greater extent of silicate partial melt extraction than other clan members, estimated to exceed 10% [2,1]. Figure 2 shows that significant silicate melt loss appears to be a prerequisite for the removal of metal. The underlying cause for greater efficiency of metal segregation in ureilites could be the greater size of the ureilite parent body, which is constrained to diameters of

>100 km by the pressure-dependent retention of C [6]. Estimates of the size of the acapulcoite-lodranite parent body, meanwhile, are in the 10's of km [2]. Greater parent body size has a two-fold effect. The first being greater thermal insulation, allowing internal portions of the body to retain radiogenic heat and reach higher temperatures (ureilites yield olivine-pigeonite temperatures of 1150-1300°C [7] while acapulcoites commonly yield 2-pyroxene temperatures in the range 1000-1150°C [8]). The second effect being increased force of gravity at a given depth below the asteroidal surface, which would enhance buoyancy driven segregation of dense metallic melts.

Conclusions: The acapulcoite-lodranite clan and ureilites are unique in that they preserve a depleted asteroidal mantle sequence that retains refractory primary metal in silicate matrix. In acapulcoite-lodranites, metal segregation is largely limited to extraction of metallic partial melts (stage 2), while ureilites appear to have experienced the removal of some of their refractory metal component (stage 3). This difference could be rooted in the larger size of the ureilite parent body. In the future, as more meteorites are recovered and more data is obtained on existing meteorites, other more underrepresented groups of stony asteroidal achondrites might yield similar sequences of refractory metals.

References: [1] Patzer A *et al.* (2004) *M&PS*, 39(1):61-85. [2] McCoy TJ *et al.* (1997) *GCA*, 61(3):639-650. [3] Mittlefehldt DW *et al.* (1998) *Rev Min*, 36(4):1-195. [4] Rushmer T *et al.* (2005) *EPSL*, 239(3-4):185-202. [5] Goodrich CA (1992) *Meteoritics*, 27:327-252. [6] Goodrich CA (2002) *LPS* 33 #1379. [7] Singletary SJ & Grove TL (2003) *M&PS*, 38(1):95-108. [8] McCoy TJ *et al.* (1997) *GCA*, 61(3):623-637.